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A cropping system assessment framework—Evaluating effects of introducing legumes into crop rotations

Moritz Reckling[a,c,*], Jens-Martin Hecker[b], Göran Bergkvist[c], Christine A. Watson[c,d], Peter Zander[b], Nicole Schläfke[b], Frederick L. Stoddard[e,1], Vera Eory[d], Cairistiona F.E. Topp[d], Juliette Maire[d], Johann Bachinger[a]

[a] *Leibniz Centre for Agricultural Landscape Research (ZALF), Institute of Land Use Systems, Eberswalder Str. 84, 15374 Müncheberg, Germany*
[b] *Leibniz Centre for Agricultural Landscape Research (ZALF), Institute of Socio-Economics, Eberswalder Str. 84, 15374 Müncheberg, Germany*
[c] *Swedish University of Agricultural Sciences (SLU), Department of Crop Production Ecology, P.O. Box 7043, 75007 Uppsala, Sweden*
[d] *Scotland's Rural College (SRUC), West Mains Road, Edinburgh EH9 3JG, United Kingdom*
[e] *University of Helsinki, Department of Agricultural Sciences, P.O. Box 27, Latokartanonkaari 5-7, 00014 Helsinki, Finland*

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A B S T R A C T

Methods are needed for the design and evaluation of cropping systems, in order to test the effects of introducing or reintroducing crops into rotations. The interaction of legumes with other crops (rotational effects) requires an assessment at the cropping system scale. The objective of this work is to introduce a cropping system framework to assess the impacts of changes in cropping systems in a participatory approach with experts, i.e., the integration of legumes into crop rotations and to demonstrate its application in two case studies. The framework consists of a rule-based rotation generator and a set of algorithms to calculate impact indicators. It follows a three-step approach: (i) generate rotations, (ii) evaluate crop production activities using environmental, economic and phytosanitary indicators, and (iii) design cropping systems and assess their impacts. Experienced agronomists and environmental scientists were involved at several stages of the framework development and testing in order to ensure the practicability of designed cropping systems. The framework was tested in Västra Götaland (Sweden) and Brandenburg (Germany) by comparing cropping systems with and without legumes. In both case studies, cropping systems with legumes reduced nitrous oxide emissions with comparable or slightly lower nitrate-N leaching, and had positive phytosanitary effects. In arable systems with grain legumes, gross margins were lower than in cropping systems without legumes despite taking pre-crop effects into account. Forage cropping systems with legumes had higher or equivalent gross margins and at the same time higher environmental benefits than cropping systems without legumes. The framework supports agronomists to design sustainable legume-supported cropping systems and to assess their impacts.

1. Introduction

Given the negative side-effects of many current agricultural practices, along with changes in both climate and international trade conditions, novel and resource-efficient production methods are needed. In Europe, less than 30% of the plant-based protein supplement fed to livestock is produced within the continent (Bouxin, 2014; Bues et al., 2013). Moreover, rotations have become very narrow and their sustainability is often questioned (Tilman et al., 2002). In order to design more sustainable cropping systems, new methods are required.

Interactions between crops are an important component of how changes in cropping systems impact on their agro-economic and environmental performance. Fertilization, nitrogen mineralization, nitrate leaching, greenhouse-gas emissions, infestations with pests, diseases and weeds, and eventual crop yield are all affected not only by the management of the individual crops but also by long-term processes that are influenced by crop sequence (Bachinger and Zander, 2007; Detlefsen and Jensen, 2007; Dogliotti et al., 2003). Thus an assessment framework is needed that considers rotational effects and systematically compares existing with novel cropping

* Corresponding author at: Leibniz Centre for Agricultural Landscape Research (ZALF), Institute of Land Use Systems, Eberswalder Str. 84, 15374 Müncheberg, Germany. Tel.: +49 3343282257.
E-mail address: moritz.reckling@zalf.de (M. Reckling).
[1] Present address: University of Helsinki, Department of Food and Environmental Sciences, P.O. Box 66, Agnes Sjöbergin katu 2, 00014 Helsinki, Finland.

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systems. Such a framework is especially needed when studying the impacts of legumes, because of their diverse impacts on cropping systems (Jensen et al., 2011; Köpke and Nemecek, 2010; Peoples et al., 2009).

Many studies have quantified rotational effects (often called pre-crop, break crop or residual effects) (see Angus et al. (2015) and Preissel et al. (2015) for recent reviews). Under European conditions, grain legume pre-crop effects are variable and increasing cereal yields by 0.5–1.6 Mg ha^{-1} Preissel et al. (2015). According to the meta-analysis by Preissel et al. (2015), the pre-crop effect of grain legumes is highest under low N fertilization to subsequent crops and comparable to non-leguminous oilseed crops.

Legume production has declined in most of Europe, from 5.8 M ha in 1961 (4.7% of arable land) to 1.8 M ha in 2013 (1.6%) (FAOstat, 2015). There are many reasons why farmers do not grow legumes, including specialization in cereal crop production, low and unstable yields (Cernay et al., 2015; Reckling et al., 2015b), and of low gross margins (Preissel et al., 2015), low and unpredictable policy support (Bues et al., 2013), and inability to recognize or evaluate the long-term benefits of legumes within cropping systems (Preissel et al., 2015). While the effect of legumes on yield of the following crop is easily measured, changes in root growth and pressures from pests and pathogens are harder to quantify. Legumes generally have lower gross margins than cereals or oilseeds, but their rotational effects increase the gross margins of subsequent crops, so assessment of legumes needs to be performed at the cropping system scale (Preissel et al., 2015) using crop rotations as the starting point. Furthermore, supply chains and markets are inadequately developed for most legume crops as shown for France by Meynard et al. (2013) except for soybean, for which the global market is well developed. Soybean areas in Europe are limited by climatic constraints, but there is considerable potential for development (de Visser et al., 2014). New varieties have been developed that are also promising under cool growing conditions (Zimmer et al., 2016).

We define a crop rotation according to Castellazzi et al. (2008) as a sequence of crops that is *fixed* (each crop follows a pre-defined order), *cyclical* (in that it repeats itself) and has a *fixed length*. The cropping system comprises the rotation, management activities (tillage, inputs, harvesting etc.) and production orientation (arable, mixed or forage). The crop rotation is considered as the starting point in cropping system analysis (Vereijken, 1997).

Bergez et al. (2010) proposed a four-step process to design cropping systems: (a) generation, (b) simulation, (c) evaluation, and d) comparison and choice. The *generation* of cropping systems and rotations can be based on existing cropping patterns, using (i) pure statistical data such as that from the integrated administration and control system (IACS) (Steinmann and Dobers, 2013), (ii) statistical data combined with rules on crop sequences (Lorenz et al., 2013; Schönhart et al., 2011), and (iii) statistical data and mathematical frameworks (Castellazzi et al., 2008; Detlefsen and Jensen, 2007). Statistical data represent current farming trends that are influenced by current policy and market drivers, but do not allow the design of cropping systems using niche or novel crops such as legumes. For this purpose another approach is required. Rule-based models are useful ways to generate novel systems (Bachinger and Zander, 2007; Dogliotti et al., 2003; Naudin et al., 2015), as they employ expert knowledge where no formal empirical data are available.

For specific, localized case studies, cropping system assessments have been conducted through *simulation* with dynamic models. Their advantage is to model soil–crop processes in detail and to simulate scenarios such as those expected under climate change. Nevertheless, they cannot be employed widely, due to their high data requirements, and they do not generate novel systems. Furthermore, crop rotations receive little consideration in dynamic models, as they are often used to assess single crops separately year-by-year not taking pre-crop effects into account (Lorenz et al., 2013). In a comparison of European crop models, Kollas et al. (2015) showed that modelling crop rotations achieves more robust results than modelling single crops, and revealed several constraints to modelling rotational effects. While most dynamic models cover soil water-related effects along with the carry-over of carbon and nitrogen in residues below and above ground, few account for crop residue quality and decomposition characteristics (Rahn et al., 2010) or the impacts on biological N fixation (BNF) of legumes and its consequences for subsequent crops. None of the models is therefore suitable for our assessment because (i) they do not generate rotations, (ii) they cannot process numerous rotations, (iii) few include carry-over effects, (iv) few model perennial crops, such as temporary grassland, (v) none incorporates soil structure effects such as soil compaction (C. Nendel Personal Communication) or break-crop effects on pests, diseases and weeds (Bergez et al., 2010), and (vi) all require detailed calibration data that is seldom available. Hence, these dynamic models are available for only a few specific case studies.

A static and rule-based approach for the *evaluation* of cropping systems without *simulation* allows a large-scale application by dealing with some of these disadvantages. (i) It makes explicit the knowledge of agronomists through the formalization of rules, (ii) requires less input data, thus allowing the inclusion of many different crops including perennials, and (iii) combines crop rotation generation and evaluation. These advantages come at the cost of less detailed results, and soil–crop processes are considered on only an annual basis. The static nature of the model means that changes in climate or management need to be implemented manually. The input of experts is required to formulate production activities and to check the plausibility of results.

The *comparison and choice* of cropping systems in the design process can be supported by multi-criteria methods (Carof et al., 2013) as shown for the design of legume-supported cropping systems in Europe (Reckling et al., 2015a).

Hence, we set out to develop a cropping system assessment framework following the process proposed by Bergez et al. (2010), excluding the simulation step, and using a static and rule-based approach considering crop rotations and rotational effects. The framework was tested by evaluating the effects of legume crops on the sustainability of agriculture by comparing cropping systems with and without legumes in two European regions, Västra Götaland in Sweden and Brandenburg in Germany.

2. The assessment framework

2.1. General approach

The framework consists of a rule-based rotation generator that comprises a fixed set of rules at the crop and rotational level and a set of algorithms to calculate the impact indicators. The application of the framework to a specific region or problem follows a three-step approach (Fig. 1): (i) generate crop rotations, (ii) evaluate crop production activities (CPA) using environmental, economic and phytosanitary indicators, and (iii) design cropping systems by combining generated rotations with evaluated CPA, and assessing their impacts.

To apply the framework, experts play an essential role: (i) agronomists define input variables such as crops, restriction values for rotation generation, and CPA, and (ii) agronomists and environmental scientists check the plausibility of evaluation results, namely the list of generated rotations and the calculated impacts, and potentially revise input values. The involvement of experts in the evaluation process is explained in more detail in Section 2.6, "framework evaluation". These experts use information and knowl-

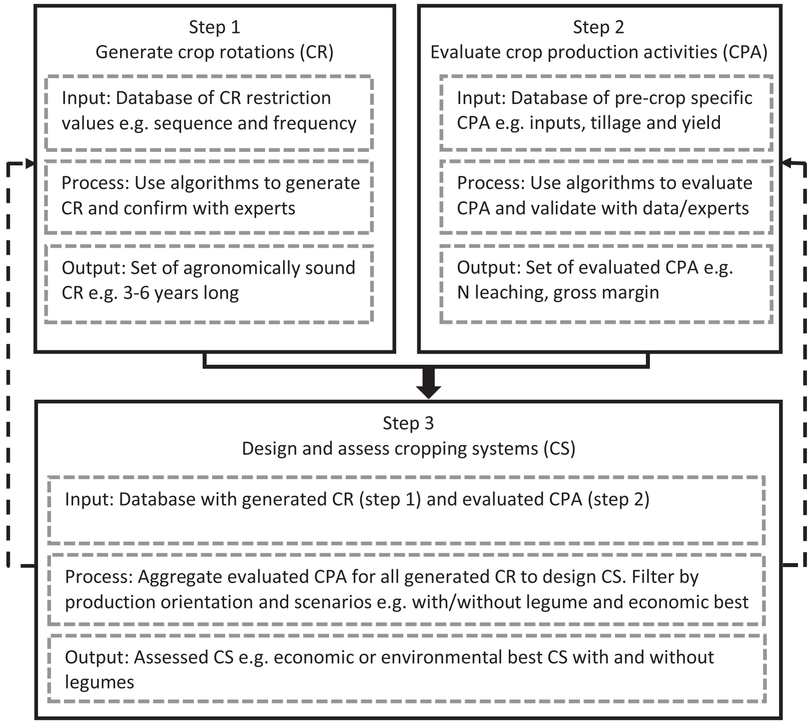

Fig. 1. Schematic illustration of the three steps in the assessment framework: step 1. generate crop rotations, step 2. evaluate crop production activities and step 3. assesscropping systems. Solid arrows represent the assessment process and dashed arrows the feedback loops after evaluation of the modelled outputs by experts.

edge from farm practice, experiments, crop management statistics and existing cropping patterns as well as literature.

The framework can be applied for arable areas with annual and perennial, non-permanent crops including crop mixtures, cover crops, under-sowing and different management systems including novel cropping and low-input systems, organic farming and conservation agriculture. The first steps before a new application are to define: (i) the region studied and sub-sites, (ii) the management system to be considered, (iii) indicators (and revise proposed indicators) appropriate to the research objective and local conditions or problems.

2.2. Generating crop rotations

The rotation generator is static, rule-based and designed to produce ‘agronomically sound rotations’, according to a set of rules and restrictions that are defined by local agronomists.

2.2.1. Restrictions for the generation of crop rotations

Site and rotational restrictions describe the suitability of crops for different soils and the extent to which the choice of crops is limited by timing, technical characteristics or phytosanitary impacts of the preceding crop. Firstly, currently grown and potentially novel crops are identified according to the aim of the application, and assigned to different sites such as soil types. Then, values of rotational restrictions are defined for the crop rotation rules (Table 1). Potential sources of information are local agronomists, literature (Kolbe, 2006), or crop sequence indicators (Leteinturier et al., 2006).

The rules include crop sequence and frequency restrictions. For each crop, the minimum sequential break describes the time period until the same crop may return to avoid phytosanitary problems. The maximum frequency describes the share a crop may have in a rotation to control soil-borne pests and diseases. The continuous cropping limit is relevant for temporary grassland and alfalfa that are grown for more than one year. Per crop type, the maximum frequency restricts the share of crops of the same type in a rotation to avoid specific pests and diseases. For each sequence, a score from 0 to 3 (0 = impossible combination; 1 = problematic combination; 2 = good combination; 3 = excellent combination) defines the suitability of crop–crop combinations considering phytosanitary and timing constraints to ensure no overlapping of cropping periods and sufficient time for seedbed preparation. Only those sequences with a score of ≥2 are considered for the generation.

Table 1
Rules describing crop rotations at crop, and rotation level as the basis for the rule-based generation.

Crop rotation rules	Examples of restriction values (for pea in Brandenburg)
Minimum sequential break of a crop [years]	4
Maximum frequency of a crop [%]	20
Continuous cropping limit of a crop [years]	1
Maximum frequency of crop types [%]	grain legumes = 25
Suitability of pairwise crop sequences [score]	e.g., pea-rye = 3

2.2.2. The generation process

The crop rotation generation consists of an iterative process of expert involvement and technical generation. After a first expert round where crop–soil suitability is assessed and rotational rules are defined, the rotation generator is used to combine crops to produce all possible two-crop combinations applying the crop sequence restrictions. Second, the two-crop sequences are combined into 3- to 6-year rotations, the cyclical nature of which is ensured. For the generated sequences, break and frequency restrictions of crops and frequencies for crops of the same type are applied as filters. Duplicates and multiples are removed. Then, agronomists check the plausibility of the results in comparison with the existing cropping patterns and if necessary revise the restriction values (often restrictions needed to be adapted to be less strict than first defined). Reasons for adaptation could be that certain crops are under- or over-represented due to one or more restrictions. The

Table 2
Classification of pre-crop types to consider rotational effects in the assessment.

Pre-crop type	Rotational effect on following crop	Crops per type
Type 1	No yield benefit, high fertilization demand and low N mineralization	Winter and spring sown cereals, silage and grain maize
Type 2	Medium yield benefit, reduced fertilization and medium N mineralization	Winter and spring sown oilseed rape, temporary grassland (without legumes), grain legumes (as sole or intercrops)
Type 3	High yield benefit, lower fertilization demand and high N mineralization	Forage legumes as sole crops or in mixtures with grasses (>30% legumes)

final set of agreed rotations is stored in a database for the subsequent evaluation by experts as described in Section 2.6, "framework evaluation".

2.3. Evaluate crop production activities (CPA)

2.3.1. Defining CPA

A CPA is defined as the complete set of activities related to the cultivation of a crop, starting with management of the stubble of the previous crop and ending with the harvest of the considered crop. CPA are characterized by the cropping inputs (seed, fertilizer, pesticides, irrigation), outputs (grain yield, straw yield) and the specific management (tillage system, fertilizer intensity, harvesting method, cover crops etc.). We distinguish separate CPA for different soil types and pre-crop types, so more than one CPA is available per crop. Pre-crop types are groups of pre-crops of different yield-affecting nitrogen residue levels (Table 2). In the definition of CPA, input and output data including crop yield and fertilizer applications are specific to the pre-crop type. They are defined depending on the management system and production orientation using regional statistics, expert knowledge and experimental data. The latter two sources are relevant in considering rotational effects because statistical data do not include pre-crop specific crop management.

2.3.2. Evaluating CPA

CPA are evaluated by environmental, economic and phytosanitary indicators (Table 3). These indicators were selected because of their sensitivity for the evaluation of cropping systems taking rotational effects into account. The pre-crop type influences nitrogen mineralization from the soil, and thereby nitrate-N leaching. The pre-crop type specific yield and fertilizer application also influences nitrate-N leaching, nitrous-oxide emissions and gross margins.

2.3.2.1. N balance, nitrate-N leaching and N fertilizer efficiency. N balance and nitrate-N leaching are calculated with algorithms that were developed for organic farming Bachinger and Zander (2007), so were modified to calculate the effect of mineral N fertilizer. Input data include site-specific average data on soils, precipitation and CPA.

A total N balance is calculated in kg ha^{-1} using the following equation:

$$N_{balance} = (N_{fixation} + N_{manureT} + N_{seed} + N_{fertilizer}) - (N_{removal} + N_{leaching}) \quad (1)$$

where $N_{fixation}$ is the BNF of grain and forage legumes calculated as a function of the crop yield, the N content of the crop, the crop-specific ratio of N in shoots to that in residues and roots, the percentage of N derived from the atmosphere (%Ndfa) depending on soil mineral N content using minimum and maximum %Ndfa values (Peoples et al., 2009), the percentage of legumes in crop mixtures, and the ratio of fixed N transferred to grass in grass–clover mixtures. The soil mineral N content is estimated considering N mineralization from preceding crop residues in spring, along with N inputs from plant-available N in manure and mineral N fertilizer. $N_{manureT}$ is the total N content in solid and liquid manure, N_{seed} and $N_{fertilizer}$ are the N contents in seed and fertilizer, $N_{removal}$ is the N removed from the field in the harvest (grain and biomass) and $N_{leaching}$ is the nitrate-N leaching calculated with Eq. (2).

Nitrate-N leaching is specific to the soil type, preceding crop and crop management, and is calculated in kg ha^{-1} using the following equation (adopted from Gäth and Wohlrab (1992)):

$$N_{leaching} = N_{surplus} \times L_P \quad (2)$$

where the $N_{surplus}$ is calculated with Eq. (3) and L_P is the leaching probability during the winter (mean winter precipitation divided by the water holding capacity at rooting depth and a crop-specific leaching coefficient).

$$N_{surplus} = (N_{manureP} + N_{fertilizer} + N_{mineralization} - N_{dfs}) \quad (3)$$

where $N_{manureP}$ is the plant-available N content in solid and liquid manure and $N_{mineralization}$ is calculated as a function of the total organic N content (typical contents per soil type) and a region-specific mean annual mineralization rate modified by the pre-crop specific N supply level. N_{dfs} is the nitrogen derived from soil (Ndfs) calculated as the N uptake minus the nitrogen derived from the atmosphere (Ndfa).

To assess the N fertilizer efficiency of all CPA in a rotation, the ratio of the N output (N in harvested products) and the N input from external sources (mineral and organic fertilizers and N in seed) is calculated. N inputs from N fixation are not included.

2.3.2.2. Nitrous oxide emissions. The soil-based N_2O emissions from crop cultivation are calculated with the IPCC 2006 Tier 1 methodology (IPCC, 2006). We considered both direct and indirect N_2O emissions from applied synthetic N, manure N and crop residue N. Emissions resulting from manure deposited during grazing, from N mineralization and from organic soils were not considered. Consistent with the IPCC (2006) guidelines, the N_2O emission from biological N-fixation is assumed to be zero. Standard IPCC (2006) emission factors and parameters have been used.

2.3.2.3. Pests, disease and weed infestation risk. Crops and their sequence in the rotation determine the pest, disease and weed pressures and the options for control. Crop choice and the tillage system are considered as the main strategic tools to reduce infestations. In the assessment framework, other direct control options of managing pests, diseases and weeds that are beyond crop choice and tillage are not considered. In the present application, different tillage intensities were not included.

The present assessment considers the infestation risk of each crop concerning selected pests, diseases and weeds that are problematic for crop production and influenced by crop choice and their sequence. The assessment uses a scoring scheme with a scale of −2 (highest reduction potential) to +2 (highest potential of increase). Scores are based on expert knowledge and field experiments. Negative infestation risks are an indication for improved phytosanitary conditions that reduce the risk of agro-chemical resistance and a potential reduction of agro-chemical applications. Currently, the assessment does not influence the economic analysis.

2.3.2.4. Gross margin. Gross margins are used for the economic evaluation of CPA. These are calculated by subtracting variable costs (inputs, variable costs of machinery and services) from the total revenues per ha. Prices for arable crops are obtained from regional statistics and reference prices are calculated for forage crops that

Table 3
Assessment indicators and their characteristics used to evaluate crop production activities and cropping systems.

Assessment indicators	Input, output and application	References
Nitrate-N leaching	Input: yield, N in organic/mineral fertilizer, N mineralization from soil, water holding capacity and precipitation in winter half-year Output: nitrate-N leaching per ha and year depending on crop, site and pre-crop Application: in the ROTOR model	The German Soil Science Society (DBG) (Gäth and Wohlrab, 1992); adapted by Bachinger and Zander (2007)
Nitrous oxide emissions	Input: yield, N in organic/mineral fertilizer, fraction of above-ground residues removed Output: N_2O emissions per ha and year depending on crop, site and pre-crop Application: in national greenhouse gas inventories and emission models	Guidelines for national greenhouse gas inventories, Intergovernmental Panel on Climate Change (IPCC, 2006)
Pests, diseases and weeds	Input: expert-based infestation risks per crop Output: aggregated infestation risk for cropping systems Application: in the ROTOR model	Bachinger and Zander (2007)
Gross margins	Input: yield, inputs, management operations, prices and costs Output: gross margins in € per ha and year Application: standard measure in farm economics	Defra (2010)

are rarely traded using the method proposed by KTBL (2010). Fixed costs, interests, insurances, costs for labor, and subsidies are not taken into account to compare cropping systems without influences of the farm type and direct policy support. Rotational effects on yields and production inputs were taken into account through defining pre-crop specific CPA.

2.4. Design and assess cropping systems

The results of the evaluation of single CPA (step 2) are linked with the individual crops of generated rotations (step 1) and aggregated for the cropping system by calculating annual average values in kg, € per ha or average pest, disease or weed scores. Cropping systems can be assessed depending on the research objective, such as comparing cropping systems with and without legumes in both arable and forage-based contexts. The assessment can be used to plot environmental vs. economic variables, such as N emissions compared to gross margins, to highlight the N fertilizer efficiency of different systems, and to analyze the infestation risks with pests, diseases and weeds. This can help to identify possible benefits, trade-offs or synergies.

2.5. Software

The framework consists of a Microsoft Access database of all CPA and parameters used for the evaluation and the generated rotations. The evaluation is performed with a separate module and the crop rotation generator was developed in Python. Input and output data were exported to a spreadsheet to support discussions with stakeholders and for the graphical comparison of cropping systems. The software combination allows efficient and quick data processing, and makes input and output data explicitly available to users.

2.6. Framework evaluation

We checked the plausibility of (i) rules, (ii) rotations, (iii) evaluation of single CPA and (iv) the final outputs at the cropping systems scale. Further evaluation is limited by the lack of robust multi-criteria datasets describing crop rotations. The outputs were evaluated by 2–4 experts per region, each with at least 5 years of experience in applied agronomy and environmental sciences and with special competence in legume cropping systems and crop rotations. Local advisory services were contacted for additional input. Experts received the outputs at three stages for a structured evaluation per region:

1. Generated rotations were compared with typical crop sequences and crop proportions. The integration of legumes was checked for agronomic acceptability.
2. Agronomic performance and environmental indicators were evaluated for common crops against data from field experiments and literature at the single crop level. Outputs were also checked for plausible differences between legume and non-legume crops.
3. Assessed cropping systems were finally checked for practicable rotations, agronomic performance and environmental impacts by comparing cropping systems with high and low shares of cereals and by filtering systems with and without legumes.

The rules implemented in the crop rotation generator were compared against the two models ROTAT (Dogliotti et al., 2003) and ROTOR (Bachinger and Zander, 2007). The algorithms for nitrate-N leaching were validated by Bachinger and Zander (2007) using HERMES, a dynamic model that simulates water and soil nitrogen dynamics (Kersebaum, 1995). The IPCC method to estimate nitrous oxide emissions is acknowledged to be simple and static, so is open to criticism Philibert et al. (2012), but is widely used in GHG inventories and emission models (Berdanier and Conant, 2012; Lokupitiya and Paustian, 2006). The IPPC method has also been used to assess GHG abatement costs in Europe through increasing the use of legumes (Dequiedt et al., 2014)

Classical evaluations with observed data including annual yield variations were not possible since, the assessment was performed for regionally representative data and not at the farm or field scale. The model outputs allow comparing relative differences between different cropping systems. A sensitivity analysis for pre-crop effects was performed by changing pre-crop affected input data.

3. Testing the framework in two case studies

The principle of the assessment framework was tested using economic, environmental and agronomic data from Västra Götaland (Sweden) and Brandenburg (Germany) to compare cropping systems with and without legumes. The aim was to explore the impact of widening current cropping systems by the integration of legumes and to quantify the relative differences between the different systems. A large set of alternative crop rotations was generated to provide a range of options for identifying the environmentally and economically best systems. Furthermore, the framework allowed the identification of trade-offs and synergies for economic, environmental and agronomic criteria.

Table 4
Soil type characteristics and distribution of assessed crops per soil type.

Crops[a]	Region	Västra Götaland	Brandenburg				
	Soil type	Clay soil	Type 1	Type 2	Type 3	Type 4	Type 5
	% clay	33	25	25	20	10	8
	% sand	17	40	50	70	80	82
	share of soil type (%)	75	8	22	37	27	6
Arable non-legume crops							
Spring barley		14		9	8		
Spring oat		17		1	1		
Spring wheat		3					
Oilseed rape		2	18	14	14		
Winter rye		1	12	3	23	28	35
Winter triticale		1	4	1			
Winter wheat		12	23	39	11		
Winter barley			9	9			
Forage non-legume crops							
Silage maize		2	14	14	17	21	
Temporary grassland[b]		43					
Arable legume crops							
Faba bean		1	<1	<1			
Pea		<1		1	1	1	
Lupin					1	2	3
Forage legume crops							
Temp. grass–clover (30% clover)		P		1		1	
Alfalfa			2	1	2		
Pea–oat mixture (50% pea)		P					
Rye-vetch mixture (50% vetch)						P	
Serradella							P

[a] Crops selected for the testing of the framework. Percentages indicate the crop production as proportion of the total arable land per soil type (in Sweden for an average of 2011–2013 (SCB, 2013) and in Brandenburg for 2011 using IACS data). P: crops not grown or not covered by statistics but with a potential in future.
[b] For the assessment, we assumed no clover in the temporary grassland although low percentages of clover (<20%) are found in current practice.

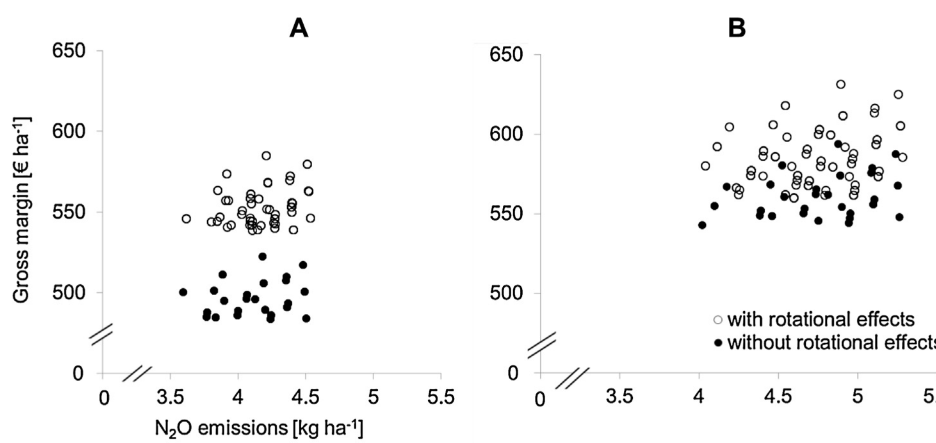

Fig. 2. Sensitivity analysis of the cropping system assessment for arable rotations in Västra Götaland. Cropping systems are assessed with and without rotational effects for cropping systems with legumes (A) and cropping systems without legumes (B).

3.1. Description of the case studies

Arable farms in Västra Götaland (Sweden) mainly cultivate cereals, and mixed farms in the same region focus on temporary grass with relatively little clover (about 20%) and cereals in their rotations. For this assessment, we assumed no clover in the grassland of cropping systems without legumes and 30% of clover in the grassland of systems with legumes. Broad-leaved crops other than legumes are grown on 6% and legumes on <2% of the arable land (SCB, 2013), so arable farms are dominated by continuous cereal cropping with few break crops. Clay soils are widespread and used by both arable and mixed farms and were therefore selected for this analysis. The wide diversity of cereals and potential novel crops allowed for the generation and evaluation of diversified systems (Table 4). According to local agronomists, the potential legume crops for arable-oriented systems were pea (*Pisum sativum* L.), pea–oat (*Avena sativa* L.) mixture and faba bean (*Vicia faba* L.), and for forage oriented systems grass–clover with higher shares of clover (>30%) than common practice.

In Brandenburg (Germany), five soil types from loam to loamy sand were distinguished, each with a different cropping pattern (Table 4). Soil types 2–4 account for 86% of the area. Arable farms are dominant on soil types 1–3, and crops are grown in short rotations. On soil types 4 and 5, the range of crops is reduced because of the low soil fertility and water availability. Potential legume crops for arable-oriented systems were faba bean, pea and narrow-leafed lupin (*Lupinus angustifolius* L.), and for mixed farms alfalfa (*Medicago sativa* L.), grass–clover, rye-vetch (*Secale cereal* L., and *Vicia* L.) and serradella (*Ornithopus sativus* Brot.).

3.1.1. Data input on rotations and crop production activities

In both regions, a structured expert survey in 2012 provided the data on CPA and captured all restriction values required for the crop rotation generator, and identified the set of legume and non-legume crops for the rotations (Table 4). These included crops that are currently grown and crops whose potential was to be assessed, as they fit into the cropping systems from an agronomic perspective despite current market conditions.

The number of selected crops, the rotational restrictions and the orientation of the systems influenced the number of generated crop rotations, ranging from none up to several thousand (Table 5). Including legumes increased the number of crops and hence the number of generated rotations. On soil types 4 and 5 in Brandenburg, no rotations without legumes could be generated because only winter rye and silage maize where assumed to be grown on these marginal soils. Typical existing rotations were added manually for soil types 4 and 5 because they were not part of the generated set but used for subsequent comparisons. Often more than one CPA was available per crop, resulting in more cropping systems than generated rotations.

For the comparison between cropping systems with and without legumes, we made the following selection: (i) in Västra Götaland, all arable rotations started with oilseed rape, winter wheat or grain legumes and had winter wheat in the second year, and (ii) in Brandenburg, all arable rotations started with winter oilseed rape except on soil types 4 and 5. Furthermore, forage systems were filtered to allow the comparison of grass–clover with (iii) temporary grassland in Västra Götaland and (iv) silage maize in Brandenburg (except on soil type 5).

To design CPA, agronomists used data from regional statistics, SJV (2011) in Västra Götaland and LELF (2010) in Brandenburg and defined pre-crop specific fertilizer application and yields using a target-oriented approach (van Ittersum and Rabbinge, 1997). In total, 77 and 138 CPA were designed for Västra Götaland and Brandenburg, respectively.

3.1.2. Indicators for disease and weed assessment

The assessment considers the infestation risk with a selected problematic disease, take-all (*Gaeumannomyces graminis var. tritici*) that affects all cultivars of wheat and barley and is especially important on winter wheat, and a problematic perennial weed, couch grass (*Elymus repens* L.) that is widespread throughout Europe, including the study regions. Both are sensitive to crop choice and are influenced by the crop rotation.

3.2. Sensitivity for rotational effects

The sensitivity analysis was performed on a selected sub-set of 100 economically best performing systems from Västra Götaland. It shows the impact of including and excluding rotational effects in the cropping system assessment on gross margins and nitrous oxide emissions (Fig. 2). From the selected data set, gross margins increased on average by 58 € ha^{-1} in cropping systems with legumes when rotational effects were included compared to an assessment without rotational effects. In cropping systems without legumes, gross margins increased by only 37 € ha^{-1}. Nitrous oxide emissions remained comparable. Therefore, rotational effects have a large impact on the assessment results. The impact is larger in cropping systems with than without legumes.

3.3. Cropping system assessments

3.3.1. Environmental vs. economic impacts

In Västra Götaland, legume-supported systems offered options with economic and environmental benefits for arable and forage systems compared to the current practice (star in Fig. 3). Arable and forage cropping systems with the highest gross margin (economic best) included oilseed rape, both with and without legumes. The environmentally best systems in terms of lowest estimated nitrous-oxide emissions with the IPCC methodology (Fig. 3C and D), were dominated by cereals. In legume-supported forages, systems with the lowest estimated nitrous-oxide emissions included grass–clover, cereals and pea–oat mixtures.

Compared to cropping systems without legumes, legume-supported arable systems had slightly lower gross margins, lower nitrate-N leaching risks and lower nitrous oxide emissions (Fig. 3A and C). When the best economic legume-supported systems were compared to best economic cropping systems without legumes and current practice, gross margins were 6% lower and 29% higher, respectively. Nitrous oxide emissions were 16% lower than in cropping systems without legumes and comparable to current practice. Nitrate-N leaching values were 7% and 11% lower, respectively. The environmentally best legume-supported system in terms of lowest nitrous-oxide emissions had 8% and 15% lower gross margins than the environmental best cropping systems without legumes and current practice. Nitrous oxide emissions were 23% and 34% lower and nitrate-N leaching 3% and 5% lower, respectively.

In forage systems, the gaps between the impact of cropping systems with and without legumes were greater for nitrous oxide emissions and lower for gross margins and nitrate-N leaching risks (Fig. 3B and D). The best economic grass–clover based systems had 4% and 15% higher gross margins than the economic best pure grass based systems and current practice. Nitrous oxide emissions were 20% and 19% lower and nitrate-N leaching 5% and 26% higher, respectively. The environmentally best legume-supported system had 28% and 41% lower gross margins than the environmentally best cropping systems without legumes and current practice. Nitrous oxide emissions were 27% and 38% lower and nitrate-N leaching 3% lower and 24% higher, respectively.

In Brandenburg, the assessment differentiated the impact of cropping systems with and without legumes for 5 soil types (Fig. 4). The current practice was economically better on all soil types than modeled alternatives, and the difference in gross margin between legume-supported systems and current practices reduced from soil types 1–5. On soil types 1 and 2, with relatively high yield potentials, legume-supported systems had the highest economic drawbacks but also the highest environmental benefits compared to cropping systems without legumes. On soil type 1, the economically best legume-supported system had 32% lower gross margins, 14% lower nitrous-oxide emissions and comparable nitrate-N leaching (not shown) than the economically best cropping system without legumes and current practice. On soil types 2–5, gross margins and nitrous-oxide emissions were on average 15% and 18% lower between the economically best legume-supported and the economically best cropping system without legumes. Nitrate-N leaching was comparable between both systems (not shown). Gross margins were negative partly because subsidies were not taken into account. Systems with forage legumes had higher gross margins, lower nitrous-oxide emissions and lower nitrate-N leaching risks compared to silage maize systems (not shown).

3.3.2. Fertilizer efficiency

In legume-supported systems, N fertilizer efficiency was higher due to the positive rotational effects of a yield increase in the subsequent crop, and because of additional input of N from BNF reducing the N fertilizer demand (Fig. 5). In arable systems in Brandenburg, the ratio of N output to N input was close to or above 1 in legume-supported and <1 in cropping systems without legumes. Systems with forage legumes had the highest N fertilizer efficiency. Grass-clover rotations had a ratio of up to 3 (excluding systems on soil type 5) and rotations without legumes around 0.6.

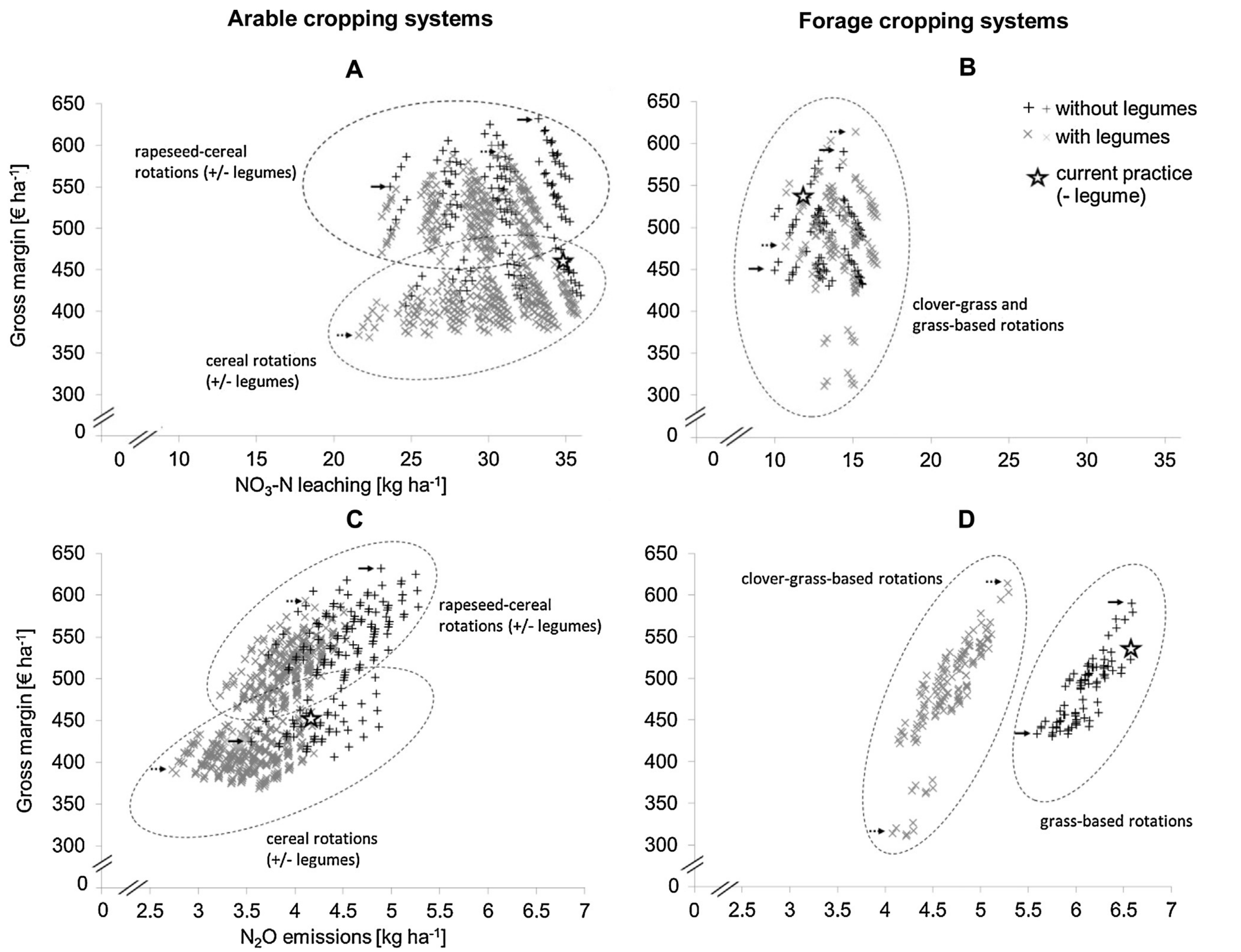

Fig. 3. Nitrate-N (NO_3-N) leaching and nitrous oxide (N_2O) emissions plotted against gross margins for cropping systems in Västra Götaland (A and C for arable and B and D for forage systems). Arrows point at the economic/environmental best performing cropping systems.

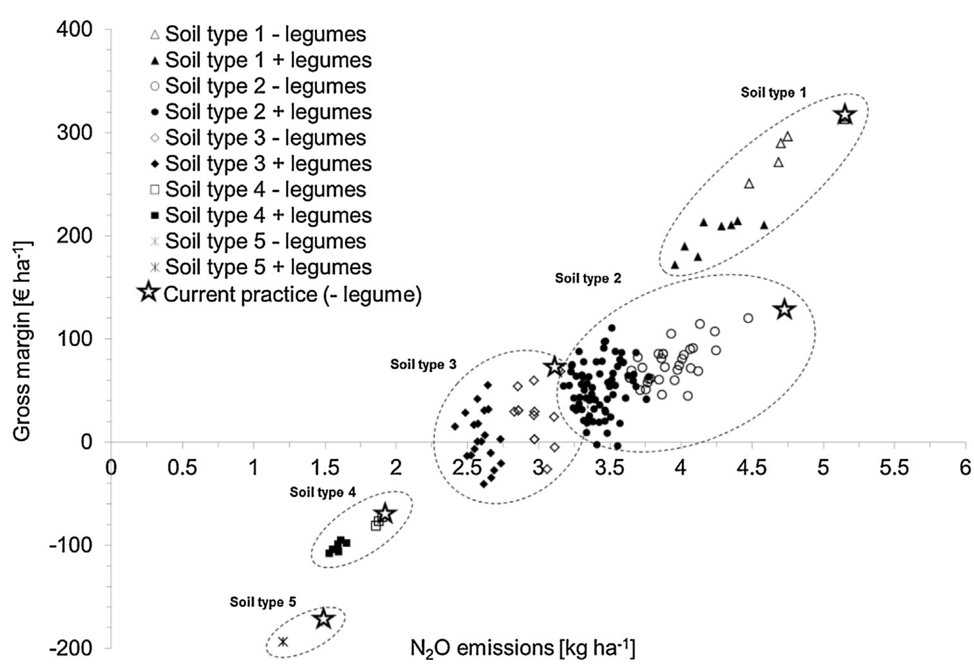

Fig. 4. Nitrous oxide (N_2O) emissions plotted against gross margins for assessed cropping systems on 5 soil types in Brandenburg.

Table 5
No. of generated rotations per site, soil type and production orientation using the rotation generator.

Crop rotation characteristics		Västra Gotaland	Brandenburg				
		Clay soil	Type 1	Type 2	Type 3	Type 4	Type 5
With legumes	Arable	5947	13	249	84	6	2
	Forage	100	97	695	310	24	9
Without legumes	Arable	1142	7	68	40	–	–
	Forage	68	27	347	88	–	–

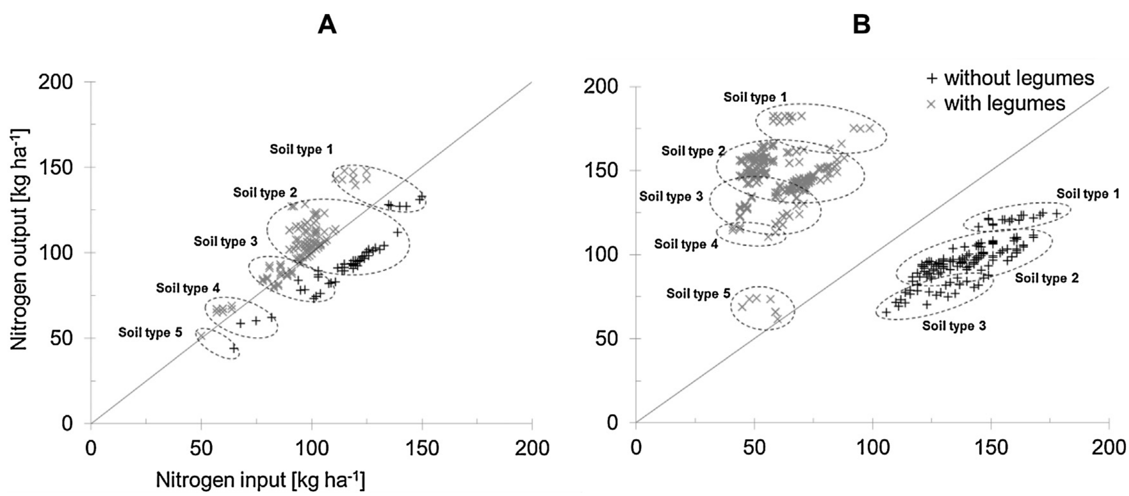

Fig. 5. Nitrogen output (harvest) plotted against nitrogen input from external sources (mineral fertiliser, manure and seed, excluding BNF) for assessed cropping systems in Brandenburg, A, arable and B, forage. The line indicates a 1:1 ratio.

3.3.3. Weed and disease infestation risk

The expert-derived assessment of selected diseases and weeds showed that the presence of legumes in arable cropping systems did not systematically change the infestation risk at the cropping system scale (not shown). In forage systems in Brandenburg, a set of data was selected to systematically compare grass–clover and alfalfa with silage maize systems on soil type 3 (Fig. 6, A). Systems with grass–clover had no infestation risk for couch grass (score of +/− 0.4) and take-all (score of 0.3 to −0.6). Systems with silage maize had an infestation risk for couch grass (score of 0.2–1.5) but not for take-all (score of 0.4 to −0.8). In Västra Götaland (Fig. 6B), grass–clover based systems had a lower infestation risk for take-all (score of −0.1 to −1) than temporary grassland (score of -0.1 to 0.6). The couch-grass infestation risks were similar in both systems (score of 0.2–1).

4. Discussion

The assessment framework successfully quantified effects of legumes at the cropping system scale that are difficult to measure, and allowed us to explore options outside the existing system configurations and boundaries. Interactions between crops were taken into account as confirmed by a sensitivity analysis (Fig. 2). Furthermore, the framework allowed a systematic comparison of cropping systems with and without legumes (Figs. 3–6). The static and rule-based approach proved to be useful. Although it might be less detailed in describing processes, it is more appropriate to the present research objective than data-driven deterministic models due to the insufficient availability of data on rotational effects to include in the models (Adams et al., 2000). The framework is especially useful in the interaction with agronomists and advisors, because it is transparent, diverse criteria are assessed (with the option to add more), and filters can help to select promising cropping systems. Selected cropping systems enable stakeholders with conflicting objectives (e.g., farmers, retailers and policy makers) to engage in a deeper discussion on trade-offs between economic and environmental impacts.

4.1. General approach of the framework

In the first step of this framework, the *generation of rotations*, the concern was to follow the logic of 'agronomist's thinking' by making their knowledge on crop rotation design explicit. This could be utilized through formalizing crop rotation rules as a basis for the generation of 'agronomic sound' rotations. The identification of restriction values revealed that agronomists tended to define very strict crop sequence and frequency restrictions, e.g., allowing only a small share of cereals that often did not allow the generation of currently widespread rotations. Hence, several iterations were needed with agronomists. The integration of additional legume crops increased the number of possible rotations considerably (Table 5). In this framework, rotations were generated on the crop scale, based on the rotational restrictions, and the evaluation of CPA was performed in a separate step. This allowed the generation of novel cropping systems in contrast to existing approaches such as ROTOR (Bachinger and Zander, 2007) that produces rotations based on a fixed set of CPA.

In the second step, *evaluating CPA*, agronomists used information from regional statistics and estimated pre-crop effects to define CPA. The strength of using expert estimations was that the pre-crop effects on yields consider factors such as root health, pests, weeds and disease that are often not considered in simulation models (Bergez et al., 2010). However, the framework is very sensitive to the estimation of pre-crop effects (Fig. 2). Soil–crop processes are considered only on an annual basis that does not allow identifying constraints during specific growth stages, such as growth limitations due to water deficit. To do so, dynamic models could provide the necessary details, but these can only model a limited number of rotations and are currently not able to simulate all relevant rotational effects (Kollas et al., 2015).

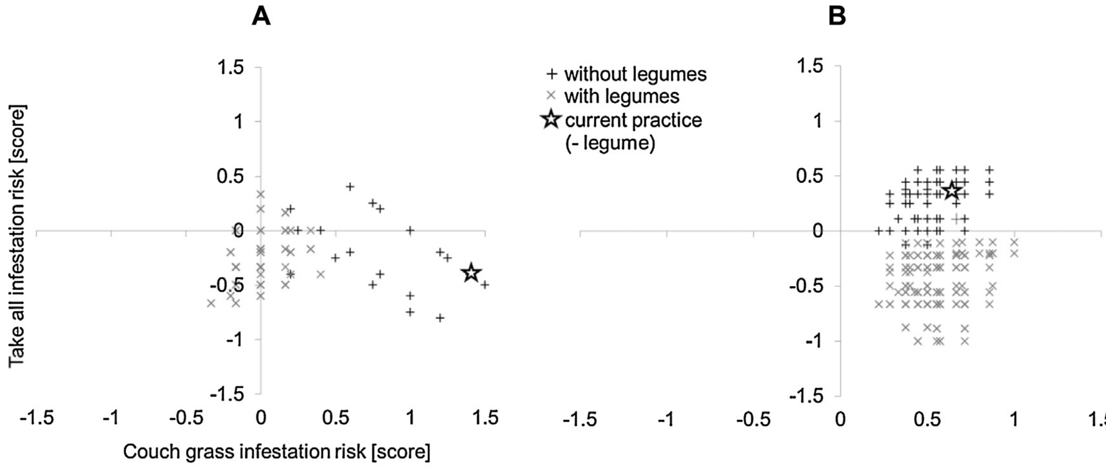

Fig. 6. Indices of take-all infestation risk plotted against couch grass infestation risk for selected forage cropping systems with a ranking from −2 to 2, where negative values indicate a reduction potential and positive values indicate an increase of the infestation risk. A: Brandenburg (soil type 3 comparing forage legumes with silage maize systems); B: Västra Götaland.

Crop rotation design is one of the major instruments applied to control weeds (Melander et al., 2005) and soil-borne pests and diseases (Vereijken, 1997). In this framework, a focus was on the most problematic species (Fig. 6), so it gives only a general indication of how the cropping system affects infestations. Results will differ depending on the species selected, so future applications will require the selection and testing of more species of pests, diseases and weeds.

The presented assessment could also be applied for other cropping systems and research objectives, such as testing with different tillage operations or cover crops. The 3-step approach allows the user to go through the steps backwards to check results on the single-crop scale. This makes the analysis transparent for users and allows efficient and early plausibility checking.

This framework requires competent agronomists to compensate for the lack of data on legume crop management, pre-crop effects and rotational restrictions. Several iterations are needed, covering data collection, design, testing and interpretation. Iterations with experts could be reduced by involving them in the modelling more actively in a participatory process or through training experts to perform some of the modelling steps themselves (e.g., the generation of rotations). Advisors could be involved more actively to increase the relevance of the assessed cropping systems.

Once the framework is designed, changes to the crop management or additional impact indicators can be added relatively easily. For example to explore impacts of soil-improving cropping systems, detailed information on soil tillage, cover crops and crop residue management would be require from experts with knowledge of agriculture in the pedo-climatic regions being studied.

4.2. Evaluation and sensitivity of outputs

The framework was evaluated using (i) design validation, (ii) plausibility checking of outputs and (iii) end-user validation as proposed by Bockstaller and Girardin (2003) and described in detail in Section 2.6. The plausibility checking, especially through experts, provided sufficient information to adapt the model for the specific applications. However, the quality of the model outputs depends to a large extent on the quality of the expert knowledge as is the case for other rule-based models (Naudin et al., 2015). Complementary to the evaluation by experts, the outputs of this static approach could be compared with measured data for specific impacts, such as N leaching, and against the outputs of dynamic models.

The major sensitivity of the application was the quantification of pre-crop effects that were estimated by experts (Fig. 2). This estimation could be improved with more robust parameters, but field experiments and dynamic models do not sufficiently provide the required data. Field experiments show that pre-crop effects vary between years and are caused by various and often cumulative factors, and dynamic models have difficulties in handling pre-crop effects (Kollas et al., 2015; Lorenz et al., 2013).

It is also important to recognize that the static calculation of nitrate leaching and nitrous-oxide emissions provides estimates that do not take into account the variability of weather, yields and environmental impacts, so are used here to make only relative comparisons. Information on the model uncertainty could improve the assessment in future.

4.3. First testing of the framework

The framework was specifically useful to assess legumes in cropping systems and to compare cropping systems with and without legumes.

The approach was able to capture positive services of legumes at the cropping system scale, namely reduced nitrous-oxide emissions, comparable nitrate-N leaching and a higher efficiency to use external nitrogen inputs due to BNF. These services have been reported for single legume crops (Jensen et al., 2011, 2010; Köpke and Nemecek, 2010; Peoples et al., 2009). In Västra Götaland and Brandenburg, nitrous-oxide emissions were lower in legume-supported systems, both arable and forage (Figs. 3 and 4). Nitrate-N leaching was comparable (Fig. 3) and a higher efficiency of N fertilizer could be achieved, especially in forage systems (Fig. 5).

At the cropping system scale, rotations with legumes were found not to increase weed or disease pressure of the selected problematic species (Fig. 6). The expert assessments showed that grass–clover reduced the infestation risk of take-all in Västra Götaland (Fig. 6B). In Brandenburg where grass–clover was compared with silage maize systems, the couch grass infestation risk could be reduced (Fig. 6A). However, some summer annual weeds might be increased by spring sown grain legumes, such as fat-hen (*Chenopodium album* L.), and legume-specific diseases, such as *Aphanomyces* root rot in pea.

The approach confirmed that the performance of legumes should be analyzed at the cropping system scale in order to capture all the benefits they provide. Arable cropping systems with grain legumes had only slightly lower gross margins than those without legumes (Figs. 3 and 4). The difference in gross margins was 6% lower in Västra Götaland and 15% lower in Brandenburg for soil type 2–5 when economic best systems were compared. Low gross margins found in usual single-crop comparisons (Preissel et al., 2015) were partly compensated by the positive pre-crop effects. In standard gross margin comparisons, rotational effects are generally not taken into account (Preissel et al., 2015). Low gross margins are a common reason for farmers not to grow legumes (Von Richthofen et al., 2006). The economic assessment at the cropping system scale is important because it substantially affects the evaluation of the economic performance of legumes. This could also influence farmers' decisions to grow legume crops.

The cropping system perspective showed that the performance of forage legumes was better than expected. Rotations with grass–clover (both sites) and alfalfa (at the more fertile soil types in Brandenburg) achieved comparable or higher gross margins than those without legumes. Reasons for the high performance of forage legumes were the high productivity, high pre-crop effects on subsequent crops and a high nutritional value of the forages. However, only reference prices could be used for calculations, because forage crops are rarely traded (except for the biofuel market), being fed to livestock on-farm. The results show that cropping systems with forage legumes could be an economically feasible alternative to current farming practices without legumes and effectively reduce environmental impacts in both regions. The evaluation of forage crops requires whole farm models such as MODAM (Zander and Kächele, 1999) for a correct assessment of their competitiveness.

An increase in legume cultivation in both regions might, however, still be constrained by agronomic challenges, in particular low yield stability (Cernay et al., 2015; Reckling et al., 2015b), legume-specific diseases, and barriers in the supply chain (Meynard et al., 2013). To overcome these challenges and increase the cultivation of legumes in Europe, the presented framework can inform on their long-term impacts in cropping systems and help to identify alternative systems to current farming practices. A particular strength of this assessment framework is that it involves stakeholders from research and practical farming in the process of redesigning and assessing cropping systems that fulfill both economic and environmental aims and that this can be done without having to test a wide range of systems on farms.

Nevertheless, changes in current farming practice require changes in socioeconomic conditions, particularly markets, consumer behavior and policy. Therefor an overall strategy is required that considers breeding, production, trading, processing and marketing to bring legumes back into European agriculture.

5. Conclusion

This paper introduced a novel framework in which it is possible to assess and systematically compare cropping systems. Its application was demonstrated for the (re) introduction of legumes in crop rotations in Västra Götaland in Sweden and Brandenburg in Germany. In the case studies, environmental impacts were lower for cropping systems with than without legumes and the economic evaluation at the cropping system scale showed benefits of systems with legumes. We demonstrated the importance of evaluating the effects of legumes in a cropping system perspective considering rotational effects.

The framework supports the design of cropping systems and assessing their impacts in a participatory approach with experts. It also supports policy makers to value the services of legumes and to bring these in relation to farm economics. The results of both case studies indicate that legumes could be exploited in cropping systems more effectively. A framework such as this can help to demonstrate how legumes could contribute to greater sustainability of agricultural systems in different regions of Europe.

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